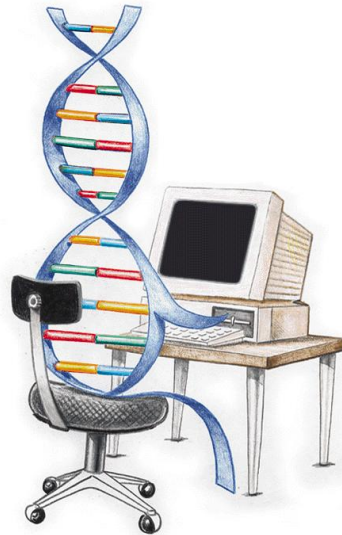# TOWARD INDUSTRIAL-STRENGTH AUTOMATED DESIGN OF ANALOG CIRCUITS BY MEANS OF GENETIC PROGRAMMING

# EH-2004—SEATTLE
# FRIDAY, JUNE 25, 2004

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# PROGRESSION OF QUALITATIVELY MORE SUBSTANTIAL RESULTS PRODUCED BY GENETIC PROGRAMMING IN RELATION TO FIVE ORDER-OF-MAGNITUDE INCREASES IN COMPUTATIONAL POWER

- **toy problems**

- **human-competitive results not related to patented inventions**

- **$20^{th}$-century patented inventions**

- **$21^{st}$-century patented inventions**

- **patentable new inventions**

# GENETIC PROGRAMMING OVER 15-YEAR PERIOD 1987–2002

| System | Period of usage | Petacycles ($10^{15}$cycles) per day for entire system | Speed-up over previous system | Speed-up over first system in this table | Human-competitive results |
|---|---|---|---|---|---|
| Serial Texas Instruments LISP machine | 1987–1994 | 0.00216 | 1 (base) | 1 (base) | 0 |
| 64-node Transtech transputer parallel machine | 1994–1997 | 0.02 | 9 | 9 | 2 |
| 64-node Parsytec parallel machine | 1995–2000 | 0.44 | 22 | 204 | 12 |
| 70-node Alpha parallel machine | 1999–2001 | 3.2 | 7.3 | 1,481 | 2 |
| 1,000-node Pentium II parallel machine | 2000–2002 | 30.0 | 9.4 | 13,900 | 12 |

# PROGRESSION OF RESULTS

| System | Period | Speed-up | Qualitative nature of the results produced by genetic programming |
|---|---|---|---|
| **Serial LISP machine** | **1987– 1994** | **1 (base)** | • **Toy problems of the 1980s and early 1990s from the fields of artificial intelligence and machine learning** |
| **64-node Transtech 8-biy transputer** | **1994– 1997** | **9** | •**Two human-competitive results involving one-dimensional discrete data (not patent-related)** |
| **64-node Parsytec parallel machine** | **1995– 2000** | **22** | • **One human-competitive result involving two-dimensional discrete data**<br>• **Numerous human-competitive results involving continuous signals analyzed in the frequency domain**<br>• **Numerous human-competitive results involving 20$^{th}$-century patented inventions** |
| **70-node Alpha parallel machine** | **1999– 2001** | **7.3** | • **One human-competitive result involving continuous signals analyzed in the time domain**<br>• **Circuit synthesis extended from topology and sizing to include routing and placement (layout)** |
| **1,000-node Pentium II parallel machine** | **2000– 2002** | **9.4** | • **Numerous human-competitive results involving continuous signals analyzed in the time domain**<br>• **Numerous general solutions to problems in the form of parameterized topologies**<br>• **Six human-competitive results duplicating the functionality of 21$^{st}$-century patented inventions** |
| **Long (4-week) runs of 1,000-node Pentium II parallel machine** | **2002** | **9.3** | • **Generation of two patentable new inventions** |

# WHAT NEXT?

- **Industrial-Strength**

# AUTOMATIC SYNTHESIS OF ANALOG CIRCUITS

"The major reason underlying this lack of analog design automation tools has been the difficulty of the problem, in our opinion. Design in the analog domain requires creativity because of the large number of free parameters and the sometimes obscure interactions between them. … Thus, analog design has remained more of an 'art' than a 'science.' "

—Balkir, Dundar, and Ogrenci (2003)

# PROMISING FACTORS

**(1) Previous runs of the six 21$^{st}$-Century patented analog circuits solved with an unusually and unexpectedly high success rate (100%)—thus suggesting that we are currently <u>nowhere near the limit</u> of the capability of existing, previously used techniques.**

# PROMISING FACTORS—CONTINUED

**(2) GP has historically demonstrated the ability to profitably exploit the relentless increase in computer power tracked by Moore's law—thus suggesting that evermore complex problems can be solved as increased computer power becomes available,**

# PROMISING FACTORS—CONTINUED

**(3) In order to emphasize the ability of genetic programming to produce human-competitive results in a relatively "clean hands" setting, previous work (intentionally) did not take advantage of elementary general domain knowledge about analog circuits**

- **We did not cull egregiously flawed circuits such as those**
  - **drawing enormous amounts of current**
  - **no connection to the circuit's incoming signals, the circuit's output ports, or power supplies**

# PROMISING FACTORS—CONTINUED

**(4) Previous work (intentionally) did not take advantage of opportunities to employ problem-specific knowledge.**

- **Genetic programming started from "scratch." However, a practicing engineer does not start each new assignment from first principles and "reinvent the wheel" on each occasion there is a need for an already known solution to a subproblem.**
- **Did not take advantage of known-useful subcircuits**

# PROMISING FACTORS—CONTINUED

**(5) The techniques used in the previous work were (intentionally) rigidly uniform**

- **We approached the design of an amplifier the same way as a filter, computational circuit, etc.**
- **No ADFs, even when there was manifest parallelism, regularity, symmetry, and modularity**

# PROMISING FACTORS—CONTINUED

**(6) Existing techniques can be improved by applying certain aspects of the theory of genetic algorithms**

- **Not very attentive to building blocks in some cases**

# PROMISING FACTORS—CONTINUED

## (7) Previous work did not take advantage of commercially available faster circuit simulation software

# PROMISING FACTORS—CONTINUED

## (8) Previous work contained some "intention-reality disparities"

# THE BAD GNU'S

**We did not consider**

- **The ultiobjective fitness measures associated with real-world design problems**
- **Corners**
- **Layout and parasitics (not covered here)**

# ULTIOBJECTIVE FITNESS MEASURES—CONTINUED

- Combining the various ("apples and oranges") elements of the fitness measure usually is vexatious
  - Amplifiers: Gain, bias, distortion
  - Local optima

# ULTIOBJECTIVE FITNESS MEASURES—CONTINUED

- Previous work rarely involved more than 4 elements in the fitness measure
- Single test fixture
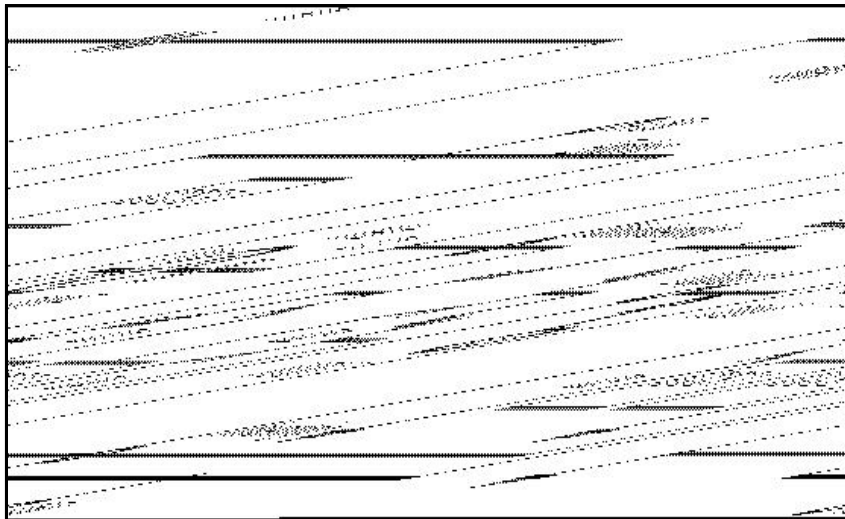
# CORNERS

- Temperature
- Variations in the power supply
- Manufacturing variations
- Loads
- Inputs
- Numerous others

- This is at least a $2^N$ impact

# LAYOUT AND PARASITICS

- **Layout**
- **Parasitics**

# BALANCING THE PROMISING FACTORS AGAINST THE COUNTERVAILING FACTORS

- **8 promising factors**
- **3 countervailing factors**

# META-ISSUES

# 2 AREAS OF TENSION

• **Inherent difference between "clean hands" approaches designed to demonstrate that evolution CAN solve a particular type of problem and "hands on" approach of practicing engineer**

• **Difficulty of extracting useful information from the literature**
   • **Red herrings**

# LM124 AMPLIFIER

- LM124 amplifier is a well-known commercial amplifier that delivers 100 dB of gain
- LM124 has 13 transistors, two resistors, one capacitor, and four current sources
- The LM124 has two inputs (an inverting input and non-inverting input) and one output
- The circuit connects to a single +5 volt power source and ground
- "Data sheet" at
`http://www.national.com/pf/LM/LM124.html`

# LM124 AMPLIFIER
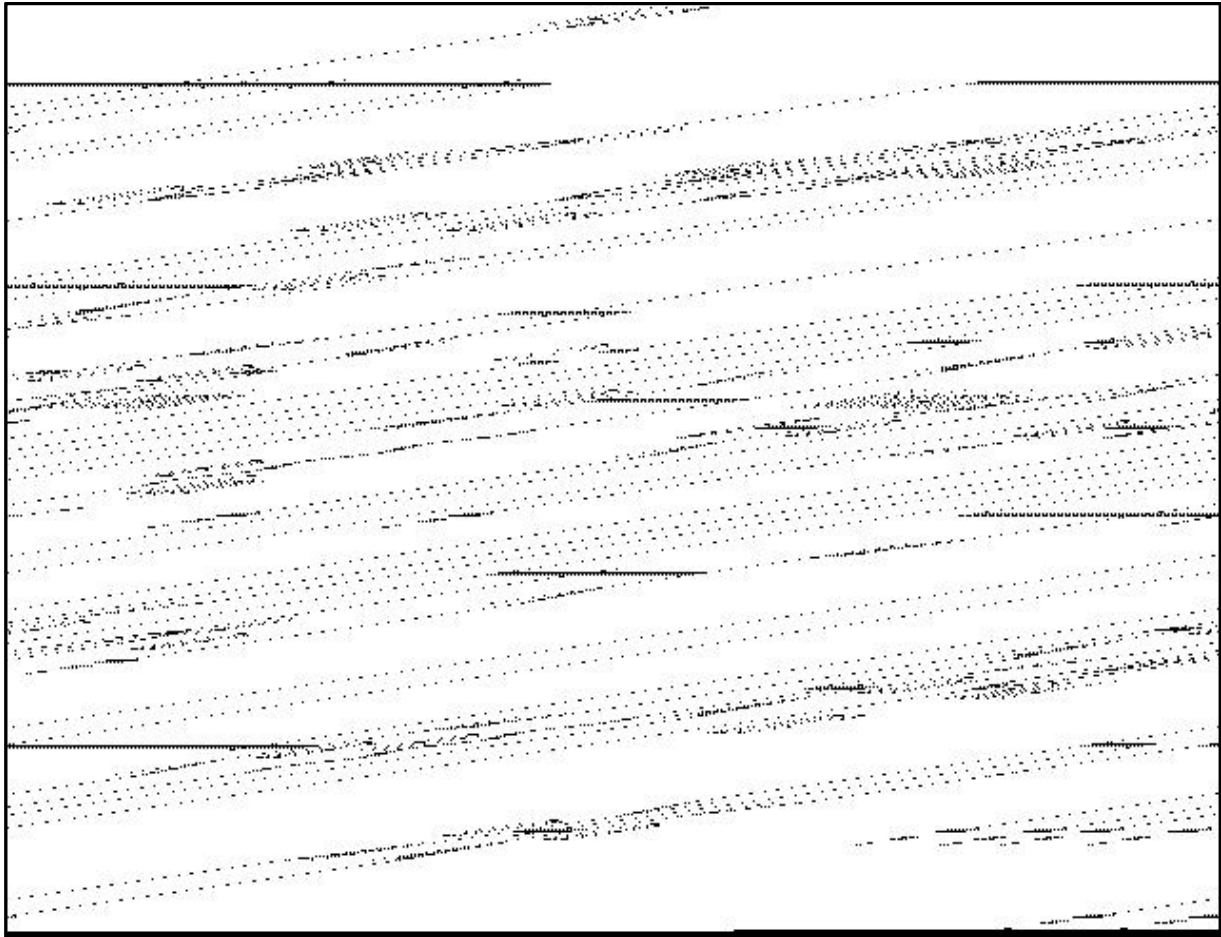
# LM741 AMPLIFIER
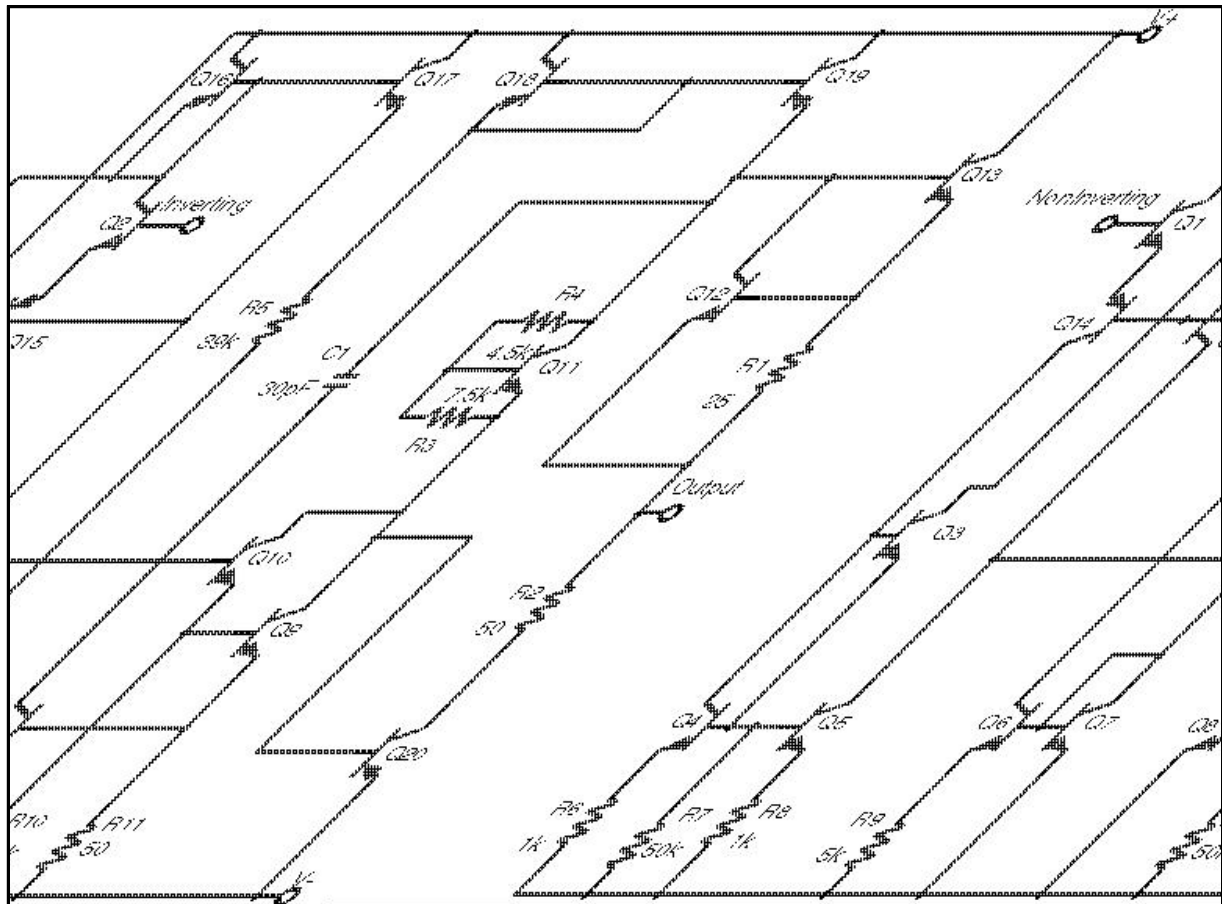
# APPROACHES—PREVIEW

- 5 ways for using elementary general domain knowledge about circuits
- 3 ways for employing problem-specific knowledge
- 8 ways of improving on previously published GP techniques
- 3 ways of grappling with multiobjective fitness measure

# APPROACHES—DETAILED PREVIEW

- **<u>5 ways</u> for using elementary general domain knowledge about circuits**
  - **Cull egregiously flawed circuits**
  - **Put useful building blocks into a library**
    - **Graeb et al. library**
  - **Narrower (only 3 orders of magnitude) range of values for resistors and capacitors**
  - **Current flow analysis (Sripramong and Toumazou 2002)**

# APPROACHES—DETAILED PREVIEW

- **3 ways** for employing problem-specific knowledge
  - Head start with a useful subcircuit
  - Use automatically defined functions
  - Put useful building blocks into a library
    - Sripramong library

# APPROACHES—DETAILED PREVIEW— CONTINUED

- **<u>8 ways</u> of improving on previously published GP techniques**
  - **Uniform treatment of 2-leaded and *N*-leaded components**
  - **Smoother topological operators (Trent McConaghy)**
  - **Topology: `VIA`, `PAIR_CONNECT`, `NODE`, `NODE_INCREASED_SCOPE` functions**
  - **Topology: `Y` division function**
  - **Insertion of transistors (Sripramong)**
  - **Dynamic Population Sizing (Sripramong)**
  - **Tie-breaking in selection (Sripramong)**
  - **Local optimization**
    - **Hill-climbing (Sripramong)**
    - **Simultaneous Perturbation Stochastic Approximation (SPSA) (J. C. Stall)**

# APPROACHES—DETAILED PREVIEW

- **3 ways** of grappling with multiobjective fitness measure
  - Identify the preeminent element of fitness measure
  - Identify elements with satisficing minimum level
  - Equalize likely contribution of remaining elements

# EXPLOITING GENERAL KNOWLEDGE ABOUT CIRCUITS

- **Cull egregiously flawed circuits (beyond the previously-handled isolated subcircuits and dangling components)**
  - **drawing enormous amounts of current**

# EXPLOITING GENERAL KNOWLEDGE ABOUT CIRCUITS

- **Also, cull egregiously flawed circuits (beyond the previously-handled isolated subcircuits and dangling components)**
  - **no connection to the circuit's incoming signals, output ports, or power supplies**

# EXPLOITING GENERAL KNOWLEDGE —CONTINUED

## • Make certain building blocks into primitive inserting functions (library)

Koza, John R. (1990). *Genetic Programming: A Paradigm for Genetically Breeding Populations of Computer Programs to Solve Problems.* Stanford University Computer Science Dept. technical report STAN-CS-90-1314. June 1990.

Koza, John R., and Rice, James P. (1991). Genetic generation of both the weights and architecture for a neural network. In *Proceedings of International Joint Conference on Neural Networks*, Seattle, July 1991. Los Alamitos, CA: IEEE Press. Volume II. Pages 397–404.

Koza, John R. (1992). *Genetic Programming: On the Programming of Computers by Means of Natural Selection.* Cambridge, MA: MIT Press.
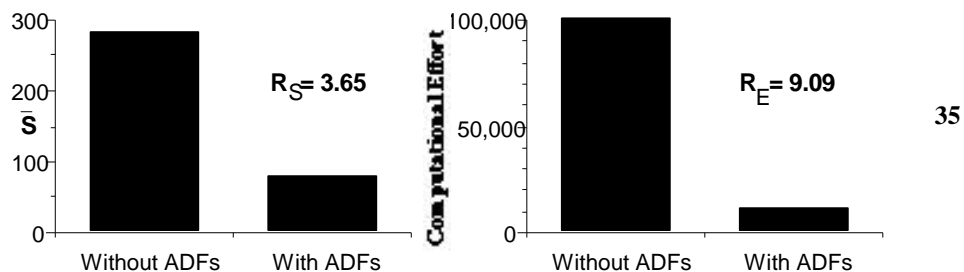
# LAWNMOWER PROBLEM WITHOUT ADF'S

# LAWNMOWER PROBLEM WITH ADF'S

300

200

$\bar{S}$

100

0

Without ADFs    With ADFs

$R_S$= 3.65

Computational Effort

100,000

50,000

0

Without ADFs    With ADFs

$R_E$= 9.09

# COMPARISON TABLE FOR THE LAWN MOWER PROBLEM – LAWN SIZE 64

|  | Without ADF'S | With ADF'S |
|---|---|---|
| Average Structural Complexity $\bar{s}$ | 280.82 | 76.95 |
| Computational Effort $I(M,i,z)$ | 100,000 | 11,000 |

# SUMMARY GRAPHS FOR THE LAWN MOWER PROBLEM – LAWN SIZE 64
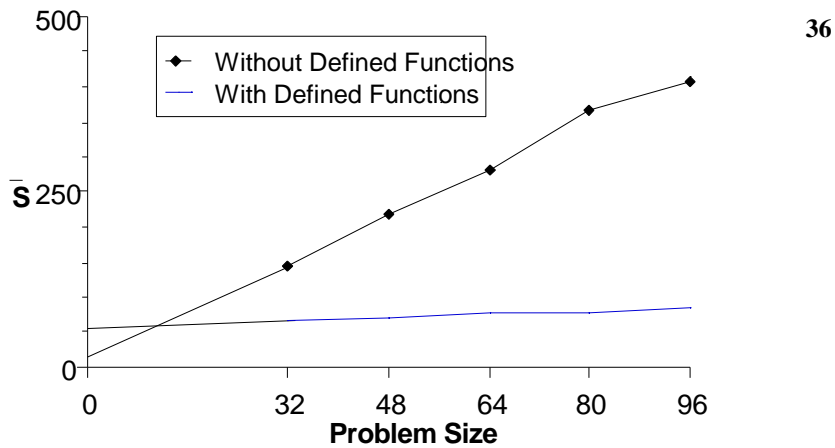
# COMPARISON OF AVERAGE STRUCTURAL COMPLEXITY OF SOLUTIONS FOR LAWN SIZES OF 32, 48, 64, 80, AND 96 <u>WITH AND WITHOUT ADF'S</u>

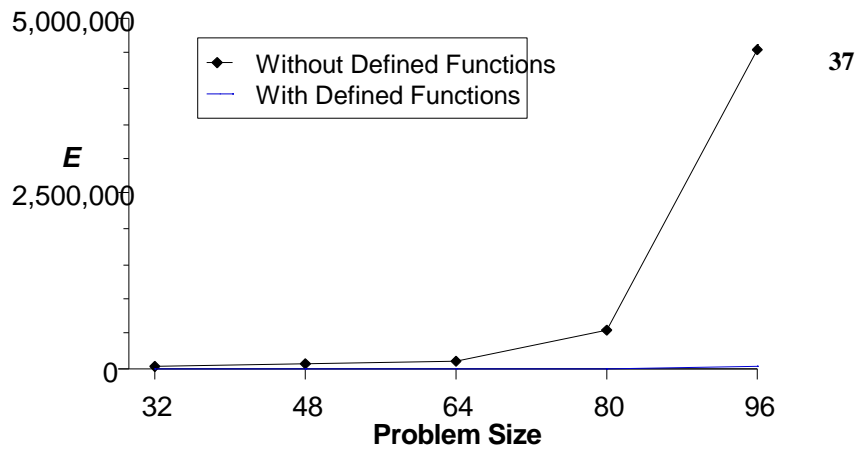|  | 32 | 48 | 64 | 80 | 96 |
|---|---|---|---|---|---|
| $\bar{S}_{without}$ | 145.0 | 217.6 | 280.8 | 366.1 | 408.8 |
| $\bar{S}_{with}$ | 66.3 | 69.0 | 76.9 | 78.8 | 84.9 |

## WITHOUT ADF'S

$S = 13.2 + 4.2L$

**Correlation $R$ of 1.00**

## WITH ADF'S

$S = 56.4 + 0.29L$

**Correlation $R$ of 0.99**

# COMPARISON OF COMPUTATIONAL EFFORT FOR LAWN SIZES OF 32, 48, 64, 80, AND 96 <u>WITH AND WITHOUT ADF'S</u>

| | 32 | 48 | 64 | 80 | 96 |
|---|---|---|---|---|---|
| $E_{without}$ | 19,000 | 56,000 | 100,000 | 561,000 | 4,692,000 |
| $E_{with}$ | 5,000 | 9,000 | 11,000 | 17,000 | 20,000 |

## WITHOUT ADF'S

$E = -2,855,000 + 61,570L$

Correlation $R$ of 0.77

$E = 944.2 * 10^{0.362 L}$

Correlation $R$ of 0.98

## WITH ADF'S

$E = -2,800 + 2.37L$

Correlation $R$ of 0.99

# EXPLOITING GENERAL KNOWLEDGE —CONTINUED

• **Graeb, Zizala, Eckmueller, and Antreich (2001) identified (for a purpose entirely unrelated to evolutionary computation) a promising set of frequently occurring combinations of transistors that are known to be useful in a broad range of analog circuits.**
• **From their set involving 2 transistors, we have implemented circuit-constructing functions that insert a**
  • **current mirror**
  • **a loaded current mirror**
  • **2 types of voltage references**
  • **a level shifter**

Graeb, Helmut E., Zizala, S., Eckmueller, J., and Antreich, K. 2001. The sizing rules method for analog circuit design. *Proceedings of the IEEE/ACM International Conference on Computer Aided Design.* Piscataway, NJ: IEEE Press. Pages 343–349.
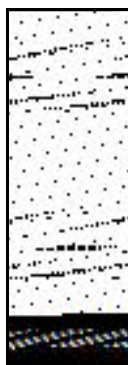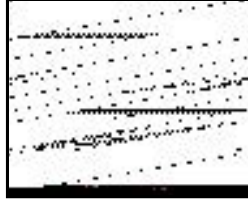
# GRAEB ET AL.—CURRENT MIRROR
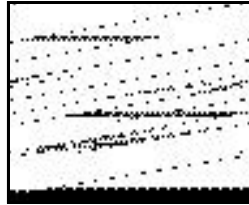


# GRAEB ET AL.—LOADED CURRENT MIRROR

# GRAEB ET AL.—VOLTAGE REFERENCES

# GRAEB ET AL.—LEVEL SHIFTER

# EXPLOITING GENERAL KNOWLEDGE —CONTINUED

- Narrower (only 3 orders of magnitude) range of values for resistors and capacitors

# EXPLOITING GENERAL KNOWLEDGE —CONTINUED

- ## Current flow analysis (Sripramong and Toumazou 2002)

Sripramong, Thanwa 2001. *The Evolution of Analogue CMOS Circuits Using Genetic Programming*. PhD thesis. University of London and Imperial College.

Sripramong, Thanwa and Toumazou, Christofer. 2002. The invention of CMOS amplifiers using genetic programming and current-flow analysis. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*. 21(11). November 2002. Pages 1237–1252.

# EXPLOITING PROBLEM-SPECIFIC KNOWLEDGE

• **Get a head start with a useful subcircuit.**

• **A differential pair that receives the inverting input and non-inverting input is a useful first stage in designing an amplifier with the characteristics of the LM124.**
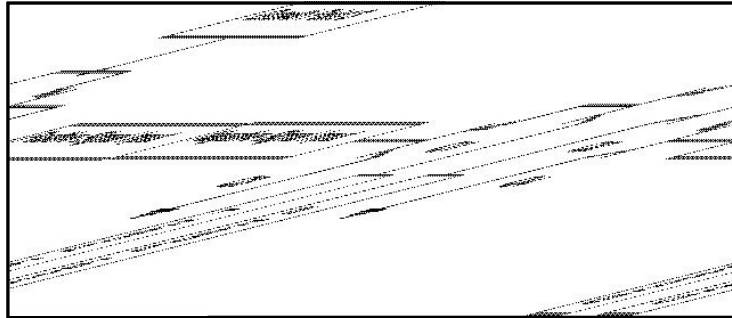


• **2 ways to implement**
  • **Hard-wired into the embryo**
  • **Hard-wired into the top of every program tree (S-expression) and then immunizing these nodes from modification by the genetic operations**

# EXPLOITING PROBLEM-SPECIFIC KNOWLEDGE

• **Reuse is pervasive in at least two of the six post-2000 patented circuits (namely the mixed analog-digital integrated circuit for variable capacitance and the low-voltage high-current transistor circuit for testing a voltage source).**

• **Use automatically defined functions (ADFs) when a problem had manifest parallelism, regularity, symmetry, and modularity.**

# EXPLOITING PROBLEM-SPECIFIC KNOWLEDGE

## • Again, make certain building blocks into primitive inserting functions (library)

Koza, John R. (1990). *Genetic Programming: A Paradigm for Genetically Breeding Populations of Computer Programs to Solve Problems.* Stanford University Computer Science Dept. technical report STAN-CS-90-1314. June 1990.

Koza, John R., and Rice, James P. (1991). Genetic generation of both the weights and architecture for a neural network. In *Proceedings of International Joint Conference on Neural Networks, Seattle, July 1991.* Los Alamitos, CA: IEEE Press. Volume II. Pages 397–404.

Koza, John R. (1992). *Genetic Programming: On the Programming of Computers by Means of Natural Selection.* Cambridge, MA: MIT Press.

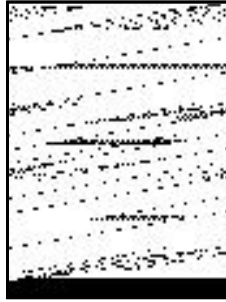# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)—PUSH-PULL
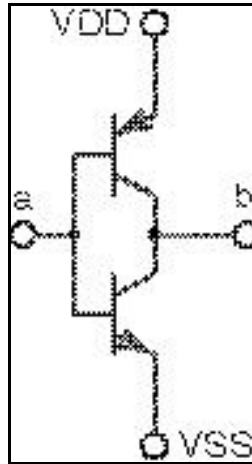


Sripramong, Thanwa 2001. *The Evolution of Analogue CMOS Circuits Using Genetic Programming*. PhD thesis. University of London and Imperial College.
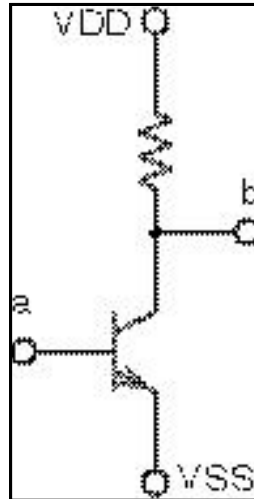
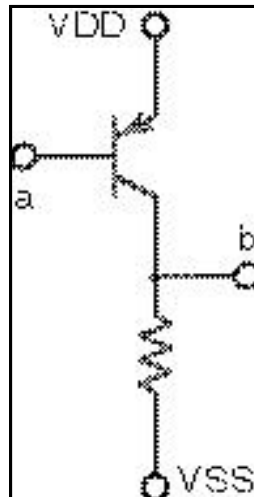# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)—*NPN* CURRENT MIRROR
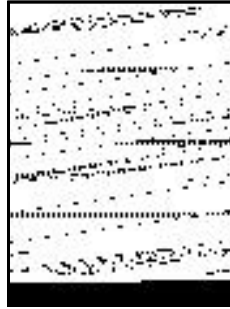
# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)—*PNP* CURRENT MIRROR

# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)—BIASED *NPN*

# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)—BIASED *PNP*

# SRIPRAMONG—GENETIC CIRCUIT LIBRARY (GCL)

| Pop # | GLC | Last Gen # | Pop Size | Complexity | MISNAMED "Comp. Effort" | Total time (sec) |
|---|---|---|---|---|---|---|
| 3 | no | 199+ | 10,000 | 42 | 2,000,000 | 183,6783+ |
| 7 | yes | 15 | 5,000 | 10 | 80,000 | 26,743 |
| 19 | yes | 17 | 5,000 | 14 | 90,000 | 32,595 |
| 31 | yes | 18 | 5,000 | 17 | 95,000 | 54,785 |

Table 4.1 Page 116 from Sripramong, Thanwa 2001. *The Evolution of Analogue CMOS Circuits Using Genetic Programming.* PhD thesis. University of London and Imperial College.

# IMPROVED GP TECHNIQUES— UNIFORM TREATMENT OF 2-LEADED AND *N*-LEADED COMPONENTS

• **All inserted components (2-leaded and *N*-leaded) are now non-modifiable after insertion into the developing circuit (eliminating asymmetry that promises to get even worse with use of the Graeb components)**

# DEVELOPMENT FOR CIRCUITS



Constructing Program Tree

Developing Circuit

In

Out
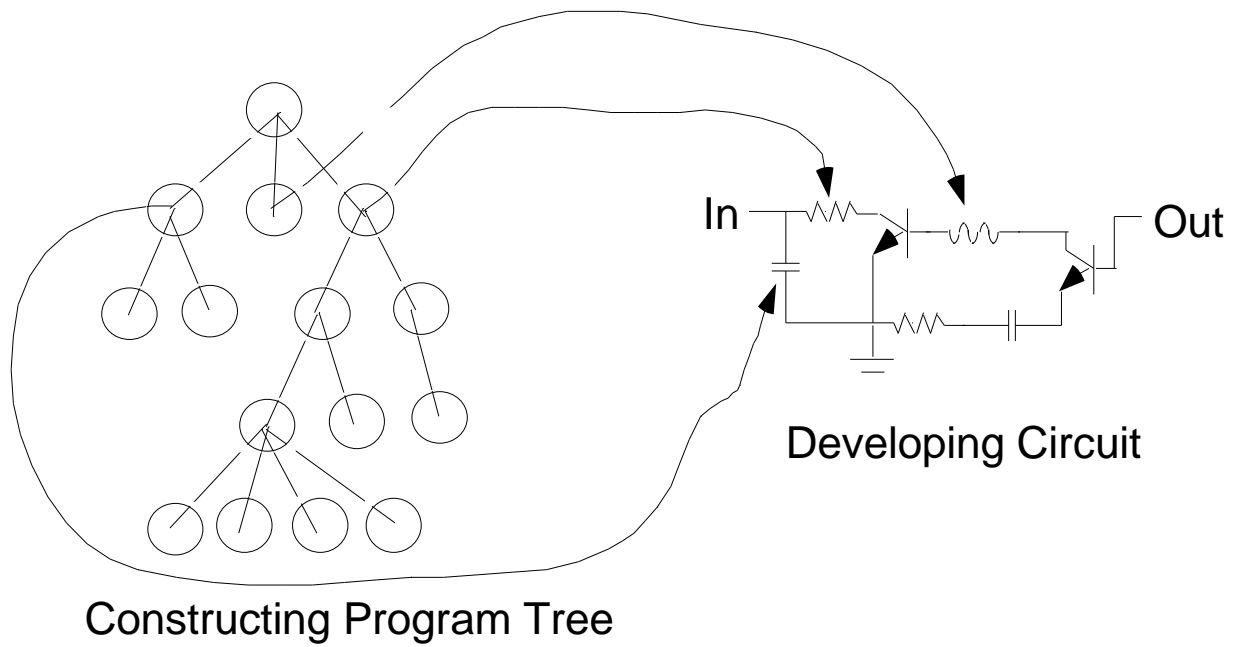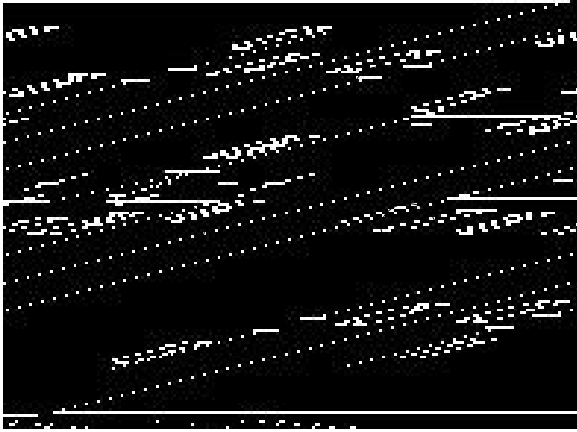
# A CIRCUIT CONTAINING A MODIFIABLE WIRE Z0
# RESULT AFTER R FUNCTION
# RESULT AFTER QT0 FUNCTION
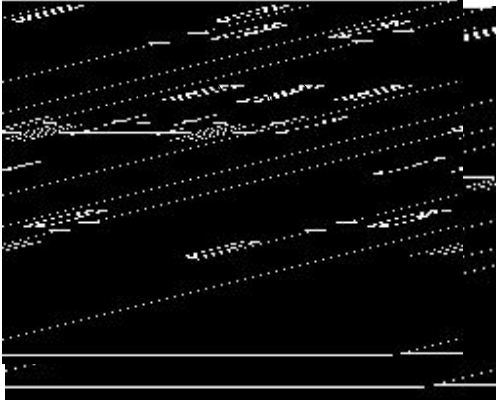
# IMPROVED GP TECHNIQUES— SMOOTHER TOPOLOGICAL OPERATORS

• The two new resistors produced by a series or parallel division to be assigned values such that the new topological composition has the same overall behavior as the original single component (Trent McConaghy)

## A CIRCUIT CONTAINING A RESISTOR R1
## AFTER THE SERIES FUNCTION

# IMPROVED GP TECHNIQUES— TOPOLOGY FUNCTIONS

- We previously used `VIA`, `PAIR_CONNECT`, `NODE` functions. Now we have `NODE_INCREASED_SCOPE` function (along with `VIA`)

- Three-argument `Y` division function

# SRIPRAMONG—APPROACHES TO INSERTING A TRANSISTOR
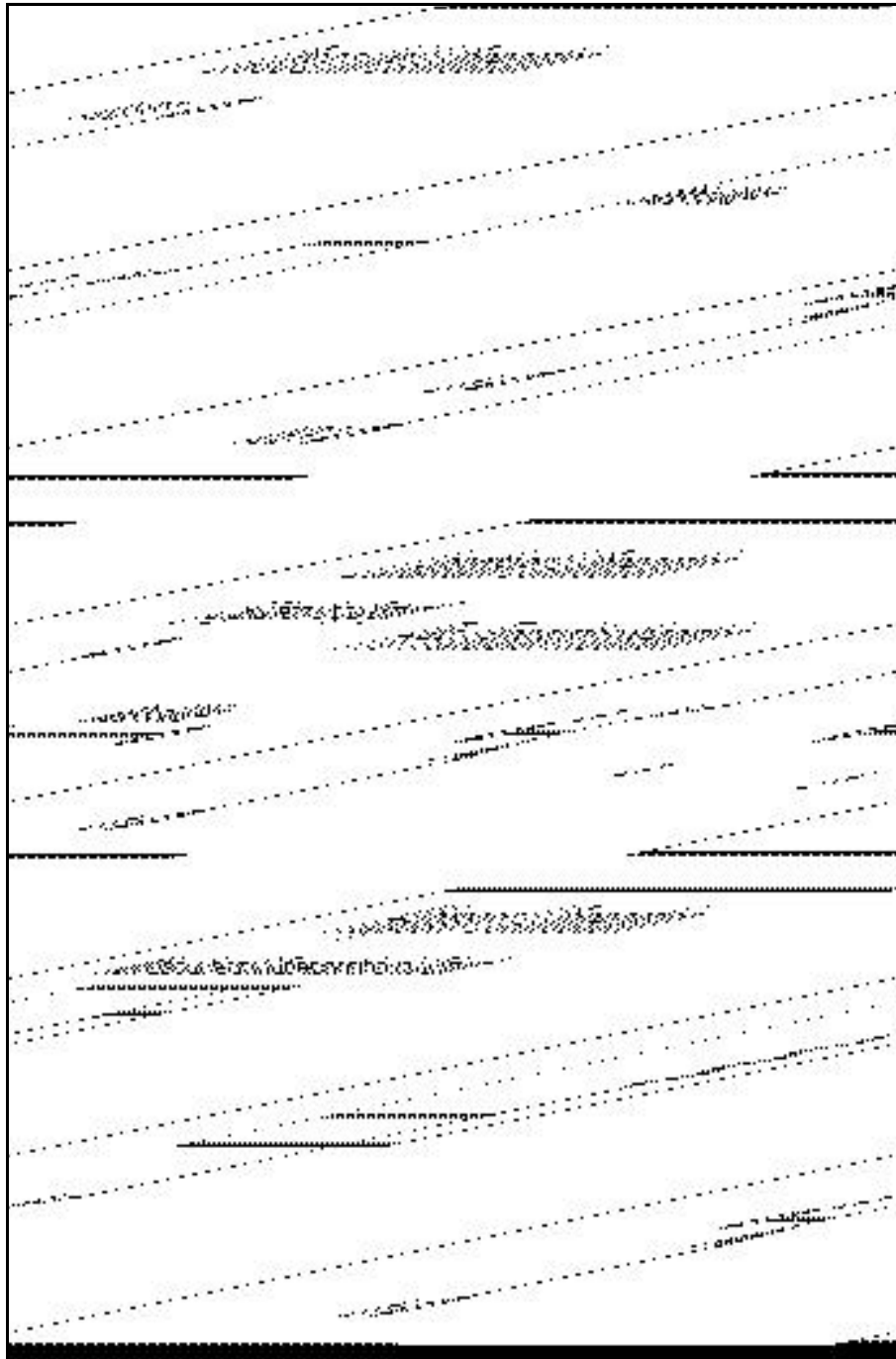
# IMPROVED GP TECHNIQUES— DYNAMIC POPULATION SIZING (SRIPRAMONG)

- **Start with smaller population (e.g., 400) at beginning of run and expand at each generation (e.g., at 5%) to larger one (e.g., 1,700)**

| Pop # | GLC | DPS | Last Gen | Last Pop Size | Com plexit y | MISNAMED "Comp. Effort" | Total time (sec) |
|---|---|---|---|---|---|---|---|
| 4 | no | yes | 108 | 1,704 | 11 | 167,086 | 72,750 |
| 8 | yes | yes | 31 | 463 | 17 | 13,193 | 5,147 |
| 32 | yes | yes | 20 | 420 | 8 | 8,720 | 4,236 |

Table 4.2 Page 118 from Sripramong, Thanwa 2001. *The Evolution of Analogue CMOS Circuits Using Genetic Programming*. PhD thesis. University of London and Imperial College.

# IMPROVED GP TECHNIQUES—TIE-BREAKING IN SELECTION (SRIPRAMONG)

- **Break ties in selection process by looking at individual with greatest improvement in fitness over its parent**

# IMPROVED GP TECHNIQUES—LOCAL OPTIMIZATION (SRIPRAMONG)

- **Hill-climbing**

# IMPROVED GP TECHNIQUES— SIMULTANEOUS PERTURBATION STOCHASTIC APPROXIMATION (SPSA) (J. C. STALL)

"The essential feature of SPSA, which provides its power and relative ease of use in difficult multivariate optimization problems, is the underlying gradient approximation that <u>requires only two objective function measurements per iteration regardless of the dimension of the optimization problem</u>. These two measurements are made by simultaneously varying in a 'proper' random fashion all of the variables in the problem (the 'simultaneous perturbation'). This contrasts with the classical ('finite-difference') method where the variables are varied one at a time. If the number of terms being optimized is $p$, then the finite-difference method takes $2p$ measurements of the objective function at each iteration (to form one gradient approximation) while SPSA takes only two measurements. A fundamental result on relative efficiency then follows: <u>One properly generated simultaneous random change of all $p$ variables in the problem</u>

**contains as much information** for optimization as a full set of $p$ one-at-a-time changes of each variable."

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE

- **The fitness measures used in previously published examples of the synthesis of analog circuits (evolvable hardware) by means of genetic programming (and genetic algorithms) typically consist of only a small handful of different elements—rarely as many as 4**
- **Previously published work typically employs only a single test fixture (test bench) to measure the circuit's fitness.**

# LM124 PROJECT

- **16 elements**
- **5 test fixtures**

# LM124 PROJECT—16 ELEMENTS

**(1) 10dB initial gain,**
**(2) supply current,**
**(3) offset voltage,**
**(4) direction cosine,**
**(5) gain ratio,**
**(6) output swing,**
**(7) output swing direction cosine,**
**(8) variable load resistance signal output,**
**(9) open loop gain for the non-inverting configuration,**
**(10) 900 KHz unity gain bandwidth for the non-inverting configuration,**
**(11) phase margin for the non-inverting configuration,**
**(12) open loop gain for the inverting configuration,**
**(13) 900 KHz unity gain bandwidth for the inverting configuration,**
**(14) phase margin for the inverting configuration,**
**(15) inversion enforcement across test fixtures for the inverting and non-inverting configurations, and**
**(16) bias current.**

# TEST FIXTURE NO. 1—NON-INVERTING CONFIGURATION
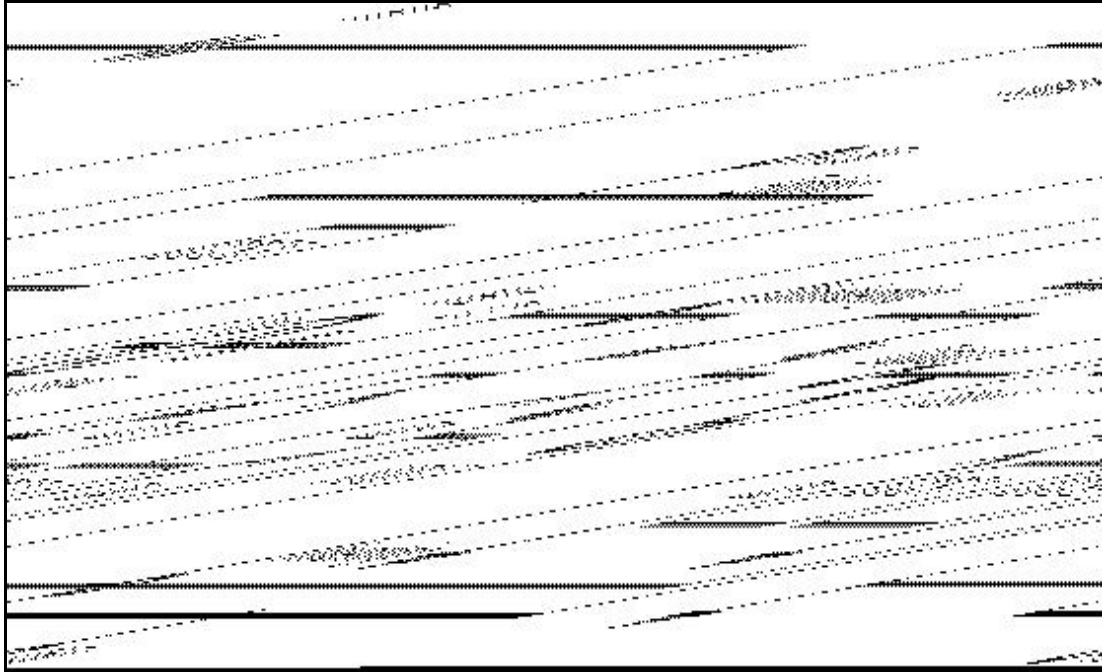


- **Open loop gain (in decibels) for the NON-INVERTING configuration**
- **900 KHz unity gain bandwidth for the NON-INVERTING configuration**
- **Phase margin for the NON-INVERTING configuration**

# TEST FIXTURE NO. 2—INVERTING CONFIGURATION
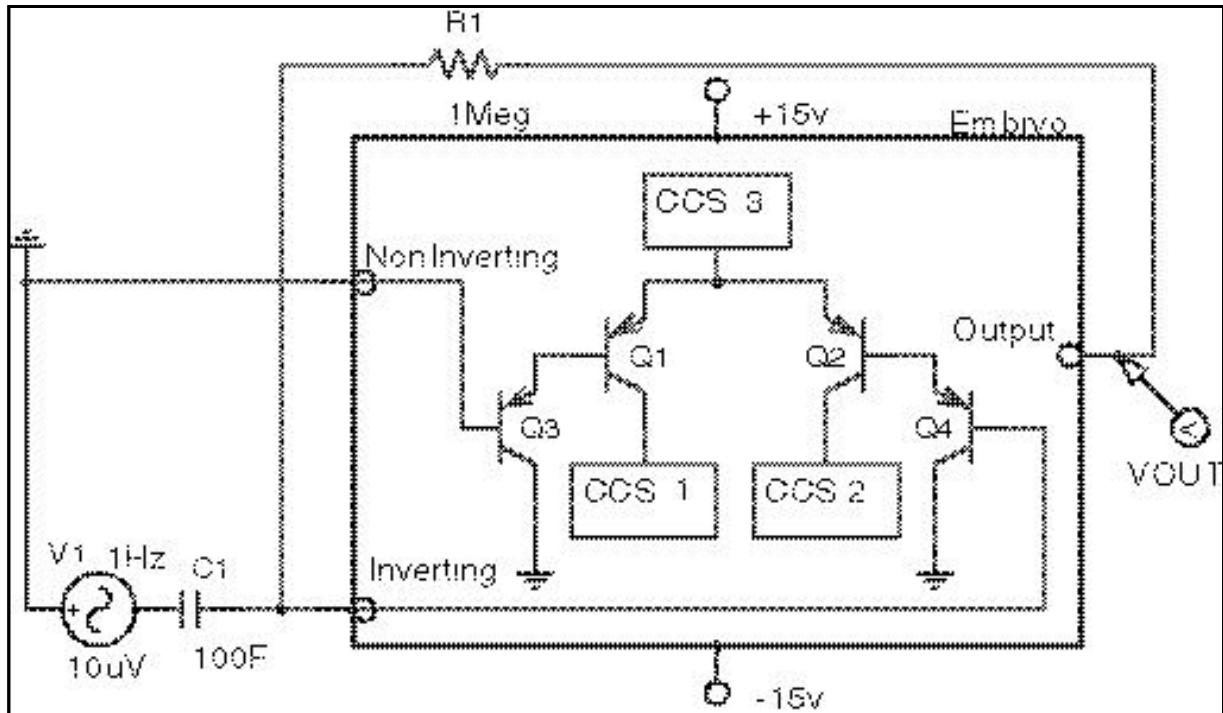


• **This test fixture differs from first one in that the inverting and non-inverting inputs are switched**

• **Open loop gain (in decibels) for the INVERTING configuration**

• **900 KHz unity gain bandwidth for the INVERTING configuration**

• **Phase margin for the INVERTING configuration**

# TEST FIXTURE NO. 3—BIAS CURRENT
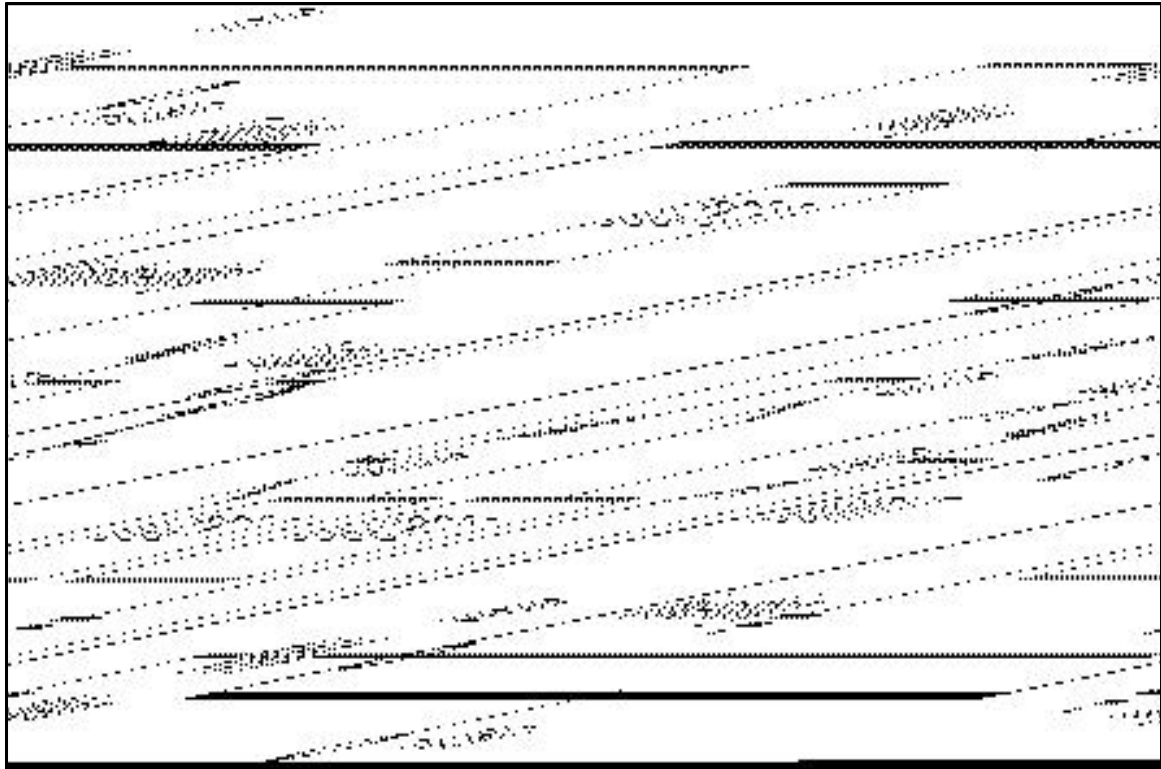


• **This test fixture differs from first one only in that there is no signal source, that there is no capacitor, and that there is a 1 mega-Ohm resistor between ground and the inverting input.**
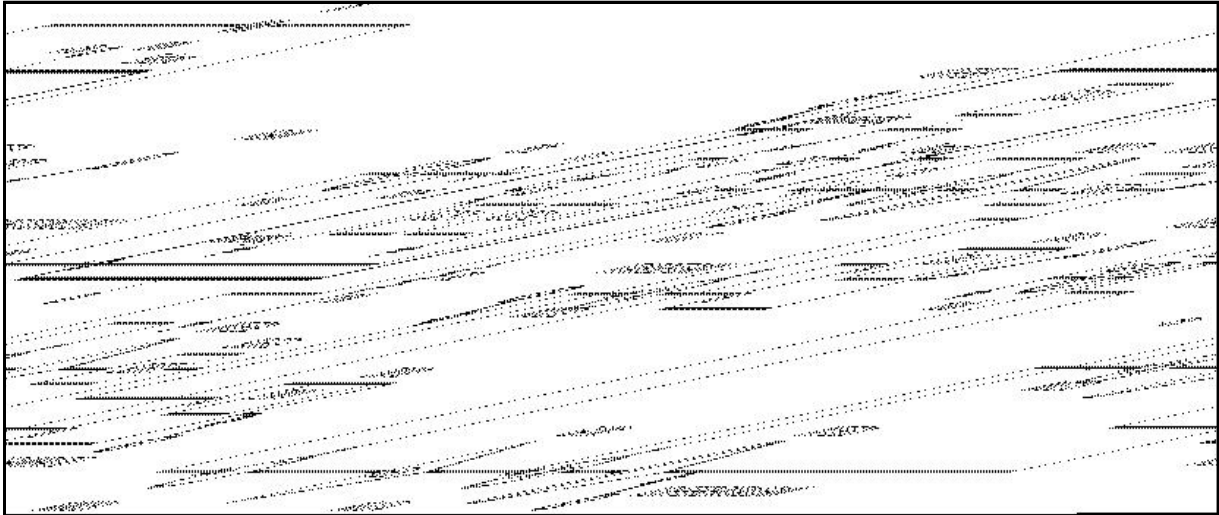
# TEST FIXTURE NO. 4— OFFSET VOLTAGE (BIAS)
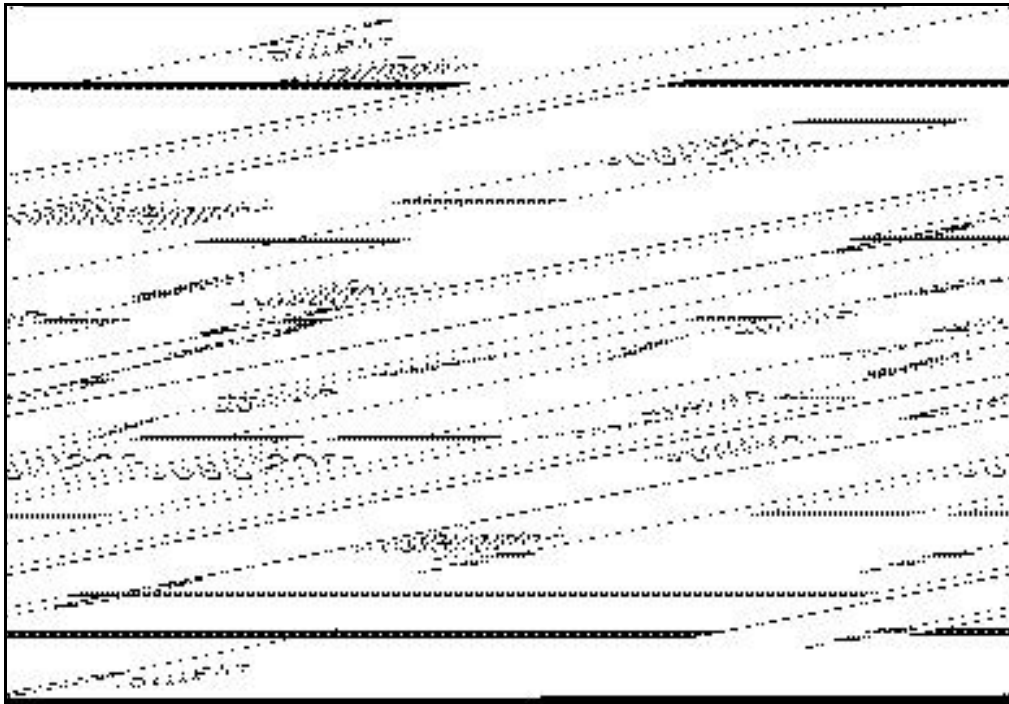


• **This test fixture differs from first one only in that there is no signal source, that there is no capacitor, and that the 1 mega-Ohm feedback resistor at the top of first figure is replaced by a wire.**

# TEST FIXTURE NO. 5—FOUR PROBE POINTS, SEVEN MEASUREMENTS, AND HARD-WIRED CALCULATIONS



- **the initial 10dB amplification**
- **output voltage under different loads (corners)**
- **direction cosine**
- **the gain ratio**
- **the offset voltage**
- **the output swing**
- **the output swing direction cosine**

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE

- **The goal to conduct an automated search (without human interaction) when one does not have any detailed information about the interrelationships among the various elements of the fitness measure**

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE— CONTINUED

• Even in such situations, one usually knows a little.

• A little information can go a long way toward constructing a serviceable fitness measure that can navigate a complex search space in a surprisingly effective way.

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE—CONTINUED

• One thing that is almost always known is the identity of the preeminent element of the fitness measure.

• Acknowledging the special role of a preeminent element of the fitness measure and disproportionately rewarding the attainment of a certain modest threshold level for that element may avoid some alluring sub-optimal basins of attractions.

• By heavily rewarding circuits that deliver as little as 10 dB of gain, one can direct the search away from the large and alluring subspace of totally degenerate circuits that deliver no gain at all (e.g., single wires) but that achieve non-zero scores for secondary elements of the fitness measure (e.g., freedom from bias and distortion).

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE—CONTINUED

• **Identify all the elements of the fitness measure for which there is no practical advantage to any improvement once some minimal level of performance has been achieved.**

• **As soon as the required minimal level is achieved for these elements, the detrimental contribution to fitness from that element should be defined to be 0 and no subsequent reward given for additional improvement.**

  • **Eliminates the potentially distracting effects of already satisfied elements of the fitness measure**

  • **Relieves the human user of the need to arbitrarily pre-specify a tradeoff between disparate elements of the fitness measure**

# THE 16 ELEMENTS ORGANIZED INTO 4 GROUPS

| Preeminent element | Amplifier-like behavior | Achievement of one required value | Time-domain signal matching |
|---|---|---|---|
| • 10dB initial gain | • Phase margin (inverting)<br>• Phase margin (non-inverting)<br>• Unity gain bandwidth (inverting)<br>• Phase and amplitude inversion<br>• Unity gain bandwidth (non-inverting) | • Desired Decibel gain (inverting)<br>• Desired decibel gain (non-inverting)<br>• Output swing<br>• Offset voltage<br>• Bias current<br>• Variable load performance<br>• Supply current | • Direction cosine<br>• Gain ratio<br>• Output swing direction cosine |

# GRAPPLING WITH A MULTI-OBJECTIVE FITNESS MEASURE—CONTINUED

• **In practice, not all measurements of fitness are completely independent. For example, the gain ratio, output swing, decibel gain, and variable load performance are all related to the amplification performance of the evolved circuit in time domain and frequency sweep contexts. The offset voltage, supply current, bias current and direction cosine are related to each other in a more subtle fashion, but all become harder to achieve as the amplification of the evolved circuit grows.**

• **The remaining elements of the fitness measure are equalized so that their expected worst case contributions are equal (arbitrarily chosen to be 30,000 here).**

# PROGRESSIVE CHANGE AMONG 8 SELECTED ELEMENTS OF THE FITNESS MEASURE
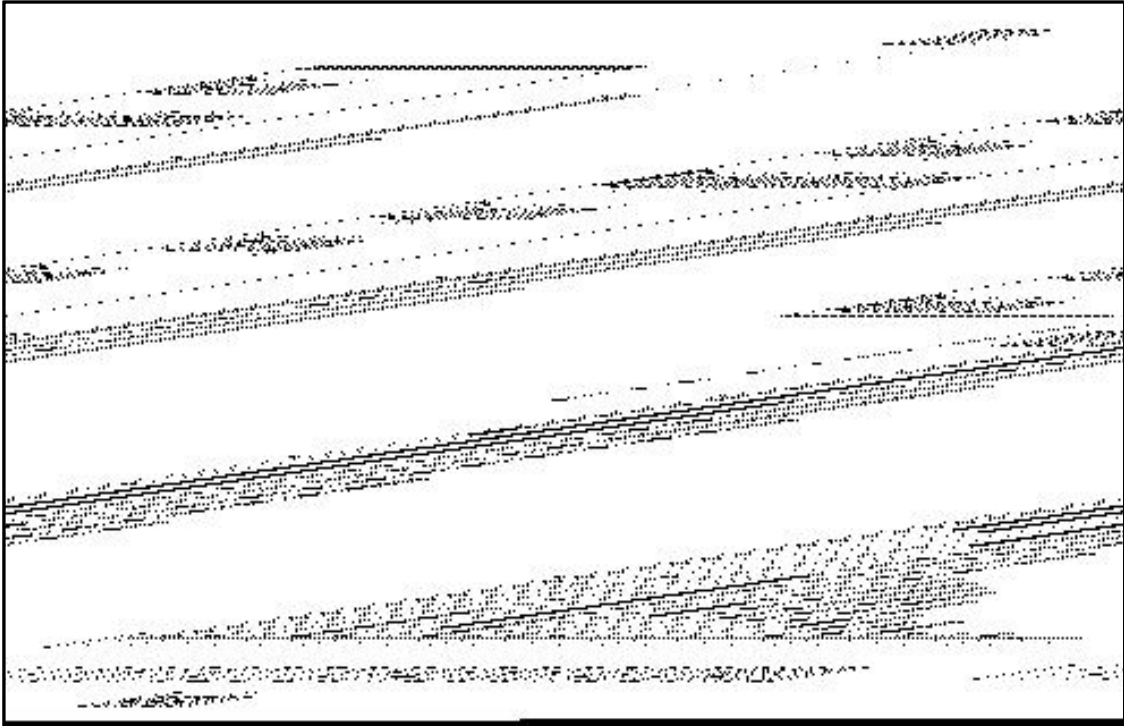
# 4 <u>OBSERVED</u> PHASES IN RECENT RUNS—40 DB AMPLFIER PROBLEM

**(1) initial topology search**
**(2) formation of a core topology**
**(3) component solution**
**(4) refinement**

# PHASE 1

● **For 40 DB, phase 1 is done by generation 1 and establishes initial topologies that deliver at least 10 dB of gain and that exhibit amplifier-like behavior (i.e., the elements of the fitness measure in columns 1 and 2)**

# BEST-OF-RUN CIRCUIT OF GENERATION 120

# PHASE 2

• **Phase 2 searches for a core topology. In generation 17, a core topology emerges that links the differential pair (Q1–Q4), a transistor (Q5), a resistor (R1), the positive power supply (V+), and the output.**

• **This topology persists for the remainder of the run.**

• **During this phase, the magnitude of each of the remaining elements of the fitness measure is substantially reduced. Although none of these elements are actually driven to 0, this phase establishes a baseline value for each of these elements for the next phase.**

# "LOGARITHMIC" BAR GRAPH OF PROGRESSIVE CHANGE AMONG ELEMENTS OF THE FITNESS MEASURE
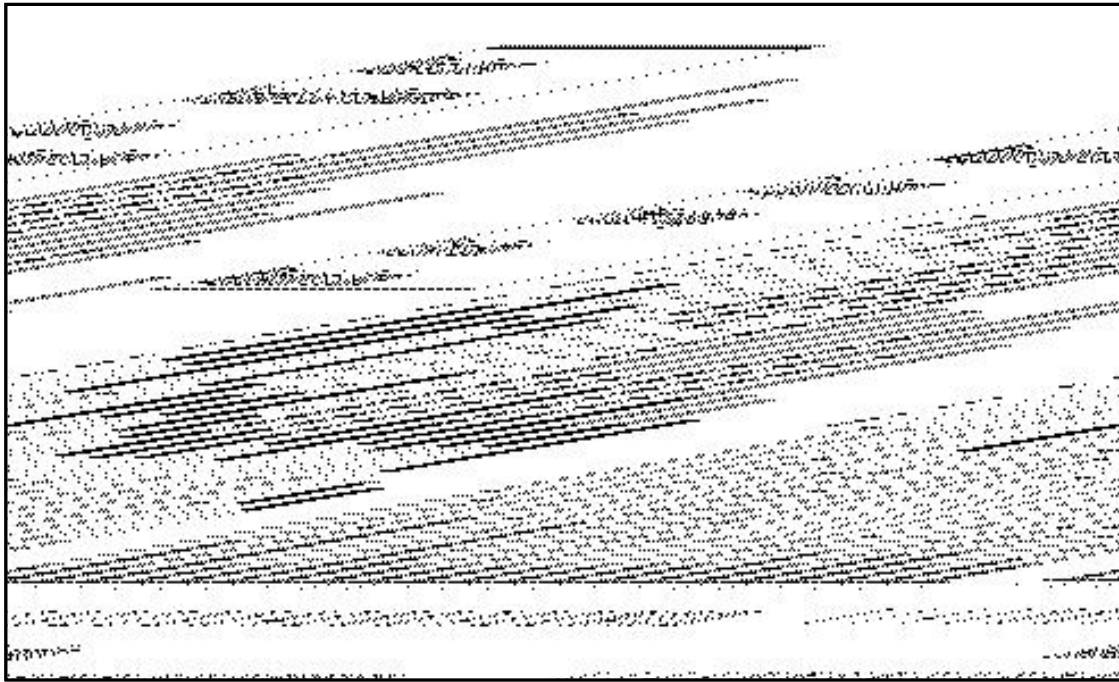
# PHASE 3

• **There are 3 sub-phases in which the run concentrates on one, two, or three elements of the six elements of the fitness measure shown in the third column.**

    • **1ˢᵗ sub-phase of phase 3: Between generations 18 and 29, a current mirror is added to the circuit to help drive the gain ratio and output swing to 0. (This then disappears).**

    • **2ⁿᵈ sub-phase of phase 3: Between generation 30 and 73, the run concentrates on offset voltage, bias current, and variable load performance (i.e., the "corners" of the load envelope). The variable load performance becomes satisfied with the addition of the current source I1 to the core topology.**

# PHASE 3—CONTINUED

- **3<sup>rd</sup> sub-phase of phase 3:** Between generation 74 and 113), the offset voltage and bias currents become satisfied. In generation 104 the bias currents are pulled below the specified values with the introduction of current source **I4**. Generation 113 sees the offset voltage satisfied by substitution of a previously placed transistor with a current mirror consisting of **Q6** and **Q7**, completing what would be the core of the solution circuit.

# PHASE 4

- **In phase 4, the remaining residual error of the fitness measure elements in the third column are pushed toward their ideal values**

# BEST-OF-RUN CIRCUIT OF GENERATION 120
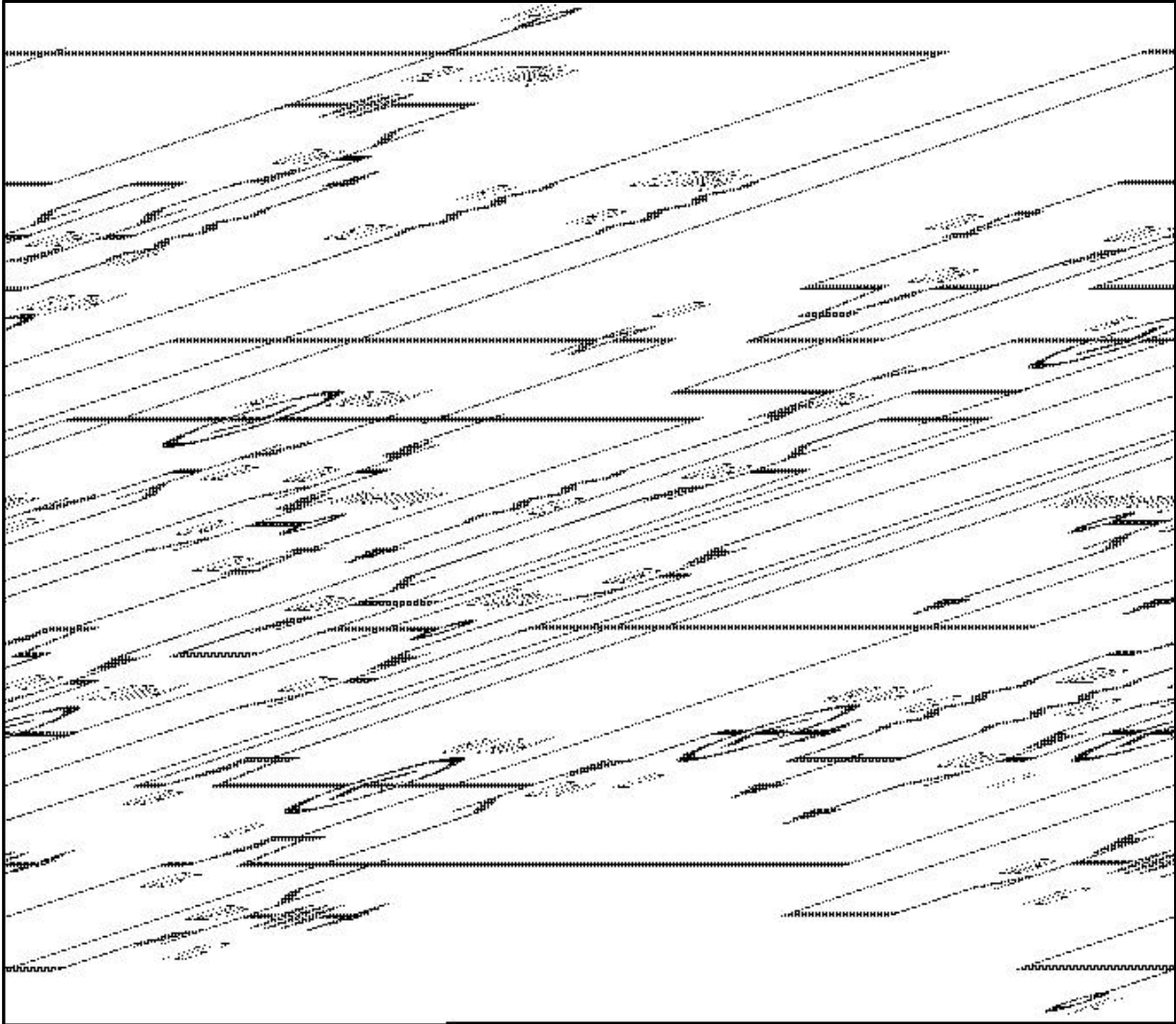
# SUMMARY FOR GRAPPLING WITH 16-ELEMENT FITNESS MEASURE WITH 5 TEST FIXTURES

• **Identify the preeminent element of the fitness measure and disproportionately reward the attainment of a modest threshold level for that element**

• **Identify all the elements of the fitness measure for which there is no practical advantage to any improvement once some minimal level of performance has been achieved.**

• **The remaining elements of the fitness measure are equalized so that their expected worst case contributions are equal (arbitrarily chosen to be 30,000 here).**

# OVERALL SUMMARY

• 5 ways for using elementary general domain knowledge about circuits

• 3 ways for employing problem-specific knowledge

• 8 ways of improving on previously published GP techniques

• 3 ways of grappling with multiobjective fitness measure

# META-ISSUES
# 2 AREAS OF TENSION

• Inherent difference between "clean hands" approaches designed to demonstrate that evolution CAN solve a particular type of problem and "hands on" approach of practicing engineer

• Difficulty of extracting useful information from the literature